Hydro-morphological characteristics and recent changes of a nearly pristine river system in Chilean Patagonia: The Exploradores river network

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Abstract

Fluvial systems provide multiple life-supporting functions, but their values are affected by a range of anthropogenic disturbances. Hydromorphology is used as a conceptual framework for assessing the status of fluvial systems and design river restoration strategies but is rarely applied to nearly pristine environments. This paper presents one of the first assessments of river characteristics and changes in the Aysen Region, an area in southern Chilean Patagonia. The analysis of multitemporal satellite images allowed to define key patterns related to river morphology of the Exploradores river network. The Exploradores basin experienced only limited and recent human disturbances, and fluvial changes are related almost only to natural climatic or geomorphological processes. The river experienced moderate reduction of active channel width and braiding index over the past 70 years. The basin represents a suitable site to study fluvial processes and dynamics in nearly reference conditions, and changes due to the likely increase of human activities and disturbances in the near future.

Keywords: rivers, Patagonia, hydromorphology, pristine system, human impacts

Introduction

Rivers and floodplains are systems of crucial importance in terms of environmental values and direct services provided to humans. It is thus important to understand the river's nature, evolutionary trajectories, and adjustments to natural and anthropogenic disturbances. In this context, hydromorphology is a conceptual framework that has been developed and then adopted (e.g. WFD, 2000/60/EU; European Commission, 2000) over the past decades to identify the complex series of characteristics and interactions between hydrological, geomorphological and ecological properties of river systems (Belletti *et al*., 2015). Because rivers are potentially severely affected by a wide range of direct and indirect human disturbances, the assessment of river hydromorphological conditions is now considered a key element for monitoring river conditions and prioritizing river restoration efforts (Rinaldi *et al.*, 2011; Wohl *et al*., 2015), especially in a scenario of increasing human pressure and adjustment to environmental and climatic changes.
Hydromorphological classifications of rivers have been generally developed for and then applied to rivers with certain degrees of direct human impacts and restoration needs (Belletti *et al.*, 2015, 2018). However, rivers adjust in complex ways to multiple and interactive direct and indirect impacts driven by climate changes, in a variety of spatial scales and temporal trajectories (Macklin & Lewin, 2019), and hydromorphological characteristics of less impacted systems are important

to be considered too. Still, hydromorphological classifications have been rarely applied to nearly pristine environments.

Although no rivers can be considered unequivocally “pristine” (e.g. Dufour & Piegay, 2009; Astorga *et al.*, 2018; Macklin & Lewin, 2019), rivers in southern Patagonia experienced relatively minor and only recent anthropogenic and environmental disturbances. The Aysén Region of Chile, located in southwestern Patagonia, features only 1.05 inhabitants per km^2, and 80% are concentrated in the few towns (Instituto Nacional de Estadísticas, INE, 2017). Only since the late 19th century, there was significant timber exploitation and livestock grazing (Simi *et al*., 2017). With no major mining operation in the region, and virtually no major hydropower projects, rivers in Chilean Patagonia suffered almost negligible direct impacts, and some are remote and almost inaccessible. For this reason, geomorphological studies on Patagonia rivers are rarely reported in literature, with the recent exceptions of the Baker (Ulloa *et al*., 2018) and the Murta Rivers (Tranmer *et al.*, 2018). However, given the growing pressure for exploitation of Chilean rivers (Andreoli *et al.*, 2012), further studies in this region are needed.

From a climatological point of view, precipitation and temperature are determined by the occurrence of ENSO and Antarctic Oscillation (Weidemann *et al*., 2018). Patagonia hosts the southern and northern Patagonian ice fields, which comprise the largest mass of ice in the southern hemisphere outside of Antarctica. Most Southern Patagonian glaciers are melting up faster than at any time in the past 350 years, with long term studies revealing a considerable mass loss (e.g. Aniya *et al.*, 2007; Malz *et al*., 2018; Foresta *et al*., 2018), with recent increase of glacial outburst floods (GLOFs) and higher likelihood of future GLOF events (Wilson *et al*., 2018; 2019). Indeed, Patagonia is increasingly subject to local pressures of development and global results of the climate change (Fajardo & Gundale, 2015; Mazzoni & Rabassa, 2013; Zagarola *et al.*, 2014) and there is a need of a better understating of the environment, in order to avoid ill-management practices in the near future.

This paper presents a first hydromorphological characterization of the Exploradores River, a basin that is likely one of the most pristine in Northern Patagonia due to the lack of terrestrial connectivity until recent years, and a very scarce human occupation and exploitation (Romero, 2017). The characterization of the hydromorphological nature of the rivers within the basin is complemented by an analysis of multitemporal changes. Physical processes such as GLOFs and natural recovery after disturbances are discussed along with the human history of colonization and exploitation of nature in the basin. It is argued that the Exploradores basin could serve as a reference site for studying natural geomorphological processes and environmental changes in a virtually unimpacted system under growing pressures due to increasing tourism and other anthropogenic activities, and also the effects of the climate change.

Physical and human geography of the study site

The Exploradores basin and river network

The study site is the Exploradores basin, located in the Aysén Region of Chilean Patagonia (approximately 46° south latitude and 73° west longitude; Figure 1). The basin hosts two important glaciers from the northern boundary of North Patagonia Ice Field (NPI), namely the Exploradores and Grosse glaciers, and many other smaller glacierized bodies. The basin area is 1452 km^2. Approximately 33% of the basin is covered by permanent snow, icefields and glaciers, and native forest (mainly *Nothofagus nítida*, *Nothofagus antártica* and *Nothofagus dombeyi*) covers 44 % of the basin (CONAF, 2013).

The basin drains to the Cupquelán fiord, and spans in elevation from 3919 (Mount San Valentín, the highest mountain in Patagonia), to 0 m a.s.l. The climate is cold temperate and humid, with a mean annual temperature of 9.1 ºC, mean minimum of 2.0 ºC (in July) and mean maximum of 19.2 ºC (in January). The mean annual precipitation is around 2000 mm and is fairly well distributed over the year. Precipitation increases with elevation; Aniya *et al*. (2007) estimated annual mean precipitation of around 3000 mm in the Exploradores Glacier.

The hydrological regime of the Exploradores River and main tributaries are characterized by a higher discharge between November and February due to snow and ice melting, followed by a gradual decrease until reaching a minimum during June. Aniya *et al.* (2007) estimated a range of discharge between 40 and 400 $m^3 s^{-1}$ in summer, and a continuous discharge of 20 $m^3 s^{-1}$ during winter. Although there are no official gauge stations with long-term records of discharge within the basin, the Exploradores basin has been subject to periodic extreme floods caused by the emptying of pro-glacial lakes or GLOFs (glacial lake outburst floods) as other rivers in the region with presence of glaciers (Marín *et al*., 2013; Iribarren *et al*., 2015). The most recent documented GLOF occurred in December 2015 at the Lago Chileno (Figure 1) located on the eastern flank of Exploradores Glacier (Wilson *et al*., 2019). A gauge station has been recently installed by DGA in the outlet of the Deshielo River, which drains the Exploradores Glacier. Further four gauging stations have been installed in 2015 in the framework of a research project (Figure 1) lead by the Catholic University of Chile.

The paleo-climatic history of Patagonia reflects a process of quick glacier melting, which intensified starting 18000 years BP. Research on the great lakes of Patagonia (General Carrera, Chacabuco and Cochrane) revealed phases of stabilization and re-glaciation that interrupted the general tendency of deglaciation (Glasser *et al*., 2016; Moreira *et al.*, 2014). Starting in the 20th century, Patagonian glaciers have shown a marked frontal retreat, thinning and surface loss (Fernández *et al*., 2010; Pasquini & Depetris, 2011; Rivera *et al*., 2012). The river network is characterized by the presence of several lakes (Figure 1). The whole basin was covered by ice during the Pleistocene (Pasquini *et al.*, 2013; Plotzki *et al.*, 2013), so the formation of lakes and rivers is the product of glacial erosion, moraine formation and other types of glacial and post-glacial sediment accumulation. From a geological point of view, the Exploradores basin features relieve of varied granite formations and Quaternary glacial deposits in the valleys (Glasser *et al*., 2016; SERNAGEOMIN, 2003).

In mountainous environments with the presence of retreating glaciers, Glacial Lake Outburst Floods (GLOFs) are likely to occur. These events are the result of a sudden liberation of great volume of water, which was previously dammed by a glacier or glacial moraine. There is evidence of this type of event in Patagonia and the great threat they pose to people and infrastructure in floodplains and valleys (Dussaillant *et al*., 2010; Iribarren *et al*., 2015; Ulloa *et al*., 2018). From a fluvial geomorphological perspective, these are events that can generate radical changes in the shape of rivers (Ulloa *et al.*, 2015). According to the glacial lake survey done by Loriaux & Casassa (2013), beyond the risk of GLOFs, glacial lakes have an important role as buffer units. As glaciers retreat, lakes formed store important volumes of water which would otherwise contribute to rising sea level.

History of human colonization in the Exploradores basin

Historically, the Aysén Region of Chile has been the most isolated region of Chile. Initially, Aysén was only accessible through sea or by land from the border with Argentina. To solve this lack of terrestrial communication, the Chilean Ministry of Public Works decided in 1967 to build the main north-south route, called the Carretera Austral (Muñoz & Torres, 2010). The route layout began in 1970 very slowly due to geographical complexities, and the construction started in 1976. As a result of late terrestrial connectivity, colonization and associated forest impacts from wildfires and agricultural development remained rather negligible up to early to mid-20th century (Astorga *et al*., 2018).

The Exploradores River Basin experimented a land ownership evolution similar to the rest of the Region of Aysén (Romero, 2017), which can be grouped in three rough stages: (1) settlement of large forestry and livestock enterprises (1900 – 1940); (2) Granting of free titles brought the first settlers, mainly farmers (1940 – 1990); (3) Population decrease, new landowners mainly large companies and enterprises (1990 – 2010).

Methods

Characterizing the fluvial geomorphology of the Exploradores river network

Due to the very limited accessibility in the basin, a first characterization of the river network was performed using remote sensing information. The hydrographic network was generated from an Aster digital elevation model using ArcGIS. The resulting river network was corrected to account for the real location of watercourses, using the existing river network map of the country (IGM, 2009). The hydrographic network was then segmented in reaches, homogenous in terms of slope, width, and morphology following a procedure adapted from Rinaldi *et al*. (2011). Major tributaries and lakes were further used to divide reaches. The basin areas and percentages of land use cover (native forest, glaciers, snow, and wetlands) were calculated for all reaches.

Using Google Earth Pro, all reaches were characterized based on different attributes related to their morphology and sizes (Table 1). The most relevant attributes are confinement degree and confinement index, which determine whether a reach is confined (C), semi-confined (SC), or unconfined (UC) as proposed by Rinaldi *et al.* (2011). Confinement degree (Gc) corresponds to the percentage of the banks that are not in contact with the floodplain, but with the valley hill slopes. On the other hand, confinement index (Ic) is the relationship between floodplain width and active channel width. The floodplain, active channel and baseflow widths were assessed on Google Earth Pro on multiple (5-8) transects equally spaced along each reach as in Henshaw *et al*. (in press) (Table 1).

Assessment of morphological changes

Historical changes of channel planform and floodplain morphology were examined using historical aerial photographs, a method widely adopted in the literature (e.g. Comiti *et al*., 2011; Picco *et al.*, 2017; Scorpio & Rosskopf, 2016; Marchese *et al*., 2017). Available photographs for the study area (Figure 2) were obtained from the Geographic Military Institute (1:40,000 scale; IGM) and the Chilean Aerophotogrametic Service (1:60,000 to 1:70,000 scale; SAF) and were complemented with ESRI satellite images (GeoEye Ikons, resolution of 1 m and precision of 25.4 m).

The first aerial photogrammetric register of Chilean territory corresponds to a United States Military Service flight made between 1943 and 1945. This flight collected photos using a trimetrogon camera, which captures one orthogonal photo and two oblique photos at 60º from the line of flight. For this study, only orthogonal photos were used, due to the excessive distortion of the oblique photos. However, very valuable information about fluvial system geomorphology can be obtained from oblique photos (Aniya *et al*., 2007; Trimble, 2012).

The IGM photos were acquired in JPG format and the SAF photos were acquired printed. The digitalization of the later was done on an Epson Expression 10,000 XL scanner at 400 dpi of resolution, they were edited using Photoshop and then exported in TIFF format to be incorporated into GIS. The sectors studied were determined based on availability of photos from the trimetrogon flight, which had lower coverage. The line of flight crosses the main watercourse in two sectors (see Figure 1). The first was located east of Bayo Lake, where the river is still called Norte River, and the second was around the confluence of the Exploradores, Teresa and Oscuro rivers (Figure 1).

To georectify the photos, a layer was created using GIS with control points (CP) corresponding to distinguishable landscape features that are constant in the period of study (important gorges, lagoon drainages and moraines). The CP were evenly distributed and the same layer was used to process all the photos in order to reduce variability. For each photo an average of 10 CPs were used, and rectified photos were defined with 3m cells. Other studies have used 5m cells for photos with 1:5000 – 1:24000 scale (Winterbottom & Gilvear, 2000) and down to 1 m cells for photos with 1:8000 – 1:30000 scale (Picco *et al.*, 2017). The mean squared error (MSE) of the rectification was on average 8.05 m, ranging between 1.48 and 14.36 m. These values are comparable to those reported by studies using similar scale photos. Using 1:15000 to 1:40000 scale photos Nicoll & Hickin (2010) obtained MSE values between 1.1 and 10. The smaller scale photos (trimetrogon 1:40000) presented the largest MSE, this was also reported by Gilvear *et al.* (2000).

Georectified photos were analyzed and areas of change (AC) were determined where there were notorious alterations between available photo years. Twelve study reaches, defined in the geomorphological classification, were identified within these AC. For each reach, in each of the four study years, the following attributes were measured: number of islands; average baseflow channel width; average active channel width and braiding index. The active channel and bankfull width were measured on transects spaced every 500 m apart, on the selected reaches (see Table 1).

Results

History of interventions in the Exploradores basin

The Exploradores basin shows late colonization in relation to the rest of the region. Indeed, the first property was registered in the 1960s. Also, the only road in the basin was initiated in 1995 and fully connected the village of Puerto Río Tranquilo (on the shores of the General Carrera Lake) to the river mouth in the Cupquelán Fiord in 2017. There are no urban areas within the basin, only sparse houses from local inhabitants, and more recently some seasonal residents.

The increased connectivity due to the construction of the road has prompted tourism in the valley, especially related to visits to Exploradores Glacier (Moreira *et al.*, 2014). Currently, 16% of the basin is privately owned, 45% state owned and the remaining 38% corresponds to Laguna San Rafael National Park (which is also a UNESCO Biosphere Reserve; Figure 3). The main economic activities are tourism and livestock grazing. Besides, aquaculture (mainly salmon farming) has gained importance within the Cupquelán Fiord over the last decade.

Direct human interventions and structures on watercourses were identified and registered in the field. Due to the limited accessibility within the basin, the only interventions are located along the axis of the dirt road that runs from the upper part of the Norte River, to the river mouth of the Exploradores River that flows into Cupquelán Fiord. This road that runs parallel to the main watercourse (Norte, then Exploradores river), from Puerto Río Tranquilo to Exploradores Bay, was completed in seven stages between 1995 and 2010. The road has 23 bridges, some stabilizing

structures (gabions) or lateral defenses, and a couple of riverbed interventions for gravel extraction, where riparian vegetation has been removed and local morphology altered due to flow diversion and gravel removal (Figure 3). Other types of minor interventions are canalizations and diversion of tributary streams parallel to the main road, but with negligible effects on the hydromorphological nature of the system. Culverts registered in this study range from simple culverts larger than 1m in diameter, multiple culverts, and culverts reinforced with concrete (Figure 4).
In terms of land cover changes, as in the rest of the region, the early settlers brought about forest-clearing practices in order to habilitate space for livestock grazing. There is evidence of forest fires along the Exploradores valley and on some hillslopes product of uncontrolled burning. Only the areas closest to Puerto Río Tranquilo present a more definitive transition from native forest to grasslands.

Hydro-morphological characterization of the river network

A total of 171 reaches were defined and characterized for their size and morphological appearance in the recent satellite images. Eleven of these reaches correspond to continental water bodies, in particular five lake/lagoons and six pro-glacial lakes including those located in front of the two main glaciers (the Grosse and Exploradores; Figure 5). The largest lake is Bayo Lake (3.7 km^2), located right upstream of the confluence with the Deshielo River. The highest water body is Teresa Lagoon, which is 2.7 km^2 and lies at 688 m a.s.l. Aislada Lagoon is the lowest lake, only at 7 m a.s.l. with 2.2 km^2. The three mentioned water bodies have been recognized as wetlands of international importance and are protected since 1981 under DS 771 (mostly an indicative national legislation). The remaining 160 reaches correspond to rivers and streams. The average reach length is 2400 m, ranging from 236 to 10500 m. Slope ranges from 0.00014 to 0.41 m m^{-1} (average of 0.082 m m^{-1}) and active channel width ranges from 3 to 300 m (average of 31 m). Table 2 shows the average values obtained for different attributes in each type of morphology defined.
Figure 6 shows that confined reaches are narrower than unconfined reaches, with median baseflow width of around 8 and 15 m, respectively, and active channel width of around 12 and 20 m, respectively. Reaches corresponding to Exploradores River close to the mouth present active channel width as wide as 300 m (Figure 6). As expected, confined reaches are steeper and have lower braiding and sinuosity indexes than semiconfined and unconfined reaches. For instance, confined reaches have slope values that range from 0.01 up to 0.41 m m^{-1}, with a median of 0.13 m m^{-1}, while unconfined reaches have an average slope of 0.01 m m^{-1} and no more than 0.05 m m^{-1}. In terms of reach morphology, most confined reaches have single-thread morphology and the braiding index is between 1 and 1.5 channel per sections, and sinuosity is on average 1.1. Unconfined reaches, located in valleys and downstream areas, have a much wider range of braiding index, going from 1 up to 6 channels per section. The sinuosity index for unconfined reaches was on average 1.8.
As expected, larger basin size results in wider active channel width, but significant difference was found between reaches with different confinement (Figure 7). The coefficients of determination (R^2) of power-law regressions for confined, semi-confined and unconfined reaches were 0.51, 0.62 and 0.72, respectively. The regressions for the glacierized and unglacierized basins provided a R^2 of 0.58 and 0.41, respectively. Interestingly, the presence of glaciers on basins increases significantly the active channel width (Figure 7).

Morphological changes

The morphological changes of river reach over time were analyzed in the two areas covered by the first aerial photos taken in 1943 (Figure 1). Overall, due to the coverage of the photos, for 12 of the 160 reaches of the Exploradores River network it was possible to follow the morphological evolution since 1943 (Table 3). Figure 8 shows close-ups images of three sectors (two downstream and one upstream, see Figure 1) within the two main areas of aerial photography analysis. The upstream sector *c* corresponds to reaches conforming the Norte River and a tributary of it, about 45 km west of Puerto Río Tranquilo along the Exploradores road. The 1943 photography shows a recent landslide on reach T_042, which delivered an important volume of sediments to the reach downstream (T_43), which appears very wide and braided. From 1943 to 2011 the T_43 reach experienced then a considerable channel narrowing, and the braiding index reduced from 3.3 to 1.9.

In the lower part of the basin (sectors *a* and *b*), the aerial photos allow observing changes of reaches T_170 and T_171 of the Exploradores River, just 10 km upstream from the river mouth in Bahía Exploradores (Figure 8). The sector *a* experienced a considerable reduction in the active channel width, the loss of some islands that appeared to have merged with the floodplain, and the progressive development of islands established on former central bars. The sector *b* appears quite dynamic over time. In 1945 there was a secondary channel creating a massive island, which later merged to the floodplain, in an area in which an aerodrome was built in the 1990's. Several small islands in the late 70's merged in a stable island by 2010. Abandoned pools and oxbow lakes dating previous to 1943 are present on sectors *a* and *b*, and appear to have been very stable over the last 70 years.

The magnitude of geomorphological changes relative to the initial aerial photo taken in 1943 study is shown in Figure 9. The baseflow channel width decreased on average 30% on all reaches, irrespective of their confinement categories, while active channel width decreased more drastically in confined channels. This can be attributed to the fact that one of the studies reaches in this category presented a very recent landslide in the 1943 photography, which generated an important sediment load downstream, resulting in an abrupt widening (Figure 8 and 9). The braiding index for the confined reaches remained mostly unchanged as most of them have single-thread morphology. Unconfined reaches show a 30% reduction in braiding index between 1943 and 2010/11.

Discussion

Natural disturbances affecting the Exploradores basin

Although no basins can be considered totally free of human impacts or disturbances, the Exploradores basin has experienced only a very recent history of human occupancy, with only punctual interventions and infrastructures, and a limited extent of land use change. This allows to consider fluvial changes related almost only to natural climatic or geomorphological processes.

Several paleo-climatic studies in Patagonia agree on identifying a reduction of precipitation and an increase in temperature over the last decades (Neukom *et al.*, 2010, 2011). There is also evidence that Patagonia is one of the regions of the world where the effects of the climate change are observed in a more acute manner, with melting of Patagonia ice fields contributing proportionally more to rising sea levels than any other ice masses of the world (Rignot *et al.*, 2003). Aniya *et al.* (2007) recently showed that the Exploradores and Grosse glaciers, although partially covered by debris, experienced retreat and thinning over the past 70 years, as most of glaciers of the Northern Patagonian Icefield.

As observed before in Chilean Patagonia, GLOF events can cause remarkable changes in the shape and processed of rivers draining glacierized basins (Ulloa *et al.*, 2015). The Exploradores River basin has previously experienced GLOF events. One of the 1943 oblique aerial photos analyzed in this study shows a pro glacial lake dammed by a lateral moraine of the Grosse Glacier which is not in place anymore (Figure 10). The lake was reported to have drained suddenly during a GLOF event in the 1970's (Bopp, A., personal communication, November 28, 2017). Also, Wilson *et al*. (2019) reported a GLOF that took place in December 2015 in the Chileno Valley triggered by a large debris-flow, and suggested that these events are likely to be more frequent in future as a result of global warming.
A more recent GLOF occurred on April 18, 2018, when the Laguna Triángulo (0.95 km^2; Loriaux & Casassa, 2013) located on the southern-most branch of the Exploradores Glacier collapsed during an intense rainfall event. The discharge generated by the event inundated several tourism infrastructures located on the Exploradores road as well as the bridge constructed over the Deshielo River (see location of the Deshielo bridge in Figure 5), which drains the Exploradores Glacier basin. In its lower part, the river has a very wide floodplain (600 m) and low slope, which allow the river to diverge and braid (average braiding index about 6). During the GLOF, the peak discharge reached above bankfull levels (Figure 11) and flowed upstream the main valley towards the Bayo Lake (see Figure 5) generating up to 2 m rise in lake level (Croxatto, F., personal communication, May 3, 2018). Given that the cross-section at the bridge is about 40 m wide and 0.035 m m^{-1} steep, considering an average water depth of about 2 m, the discharge at the time of the GLOF (assuming that the photo on Figure 11 was taken at the time of the peak) would have been at least 350 m^3 s^{-1}. The Laguna Triángulo level decreased significantly and the place of moraine rupture can be seen in recent satellite images.

The nature and changes of the Exploradores river network

Southern Patagonia is a region of high geological instabilities, and rivers are shaped by paroxistic events such as earthquakes (Mohr *et al.*, 2017), volcanic eruptions (Major *et al.*, 2016; Ulloa *et al*., 2015), GLOFs (Dussaillant *et al.*, 2010; Ulloa *et al*., 2018) which deliver sudden and large amount of water and sediments to the river systems. After high-magnitude disturbances of these kinds, river systems adjust to the changed degree of connectivity and sediment supply trough slow recovery trajectories (e.g. Ziliani & Surian, 2012). Although affected by recent GLOF events, the Exploradores basin did not experience such dramatic disturbances in the recent past, and the river network showed only a moderate reduction of the active channel width and braiding index between 1943 and 2011. Given that active channel width can be considered a proxy for river discharge (Gilvear *et al*., 2000), this decrease of width and reduction of braiding index could potentially be due to several reasons. Considering the negligible direct impacts of disturbances related to hydropower production, water extraction, in-channel gravel mining, or mineral mining, the slight reduction of baseflow and active channel widths and braiding index could be related to local sediment supply conditions (e.g. the reach T_43), and at a larger scale to aa reduction of precipitation, a decrease of glacier and snow-melt, or to a decreased sediment load.
As to the reduction of precipitation, due to the lack of long-term rainfall data collected within the basin, we focused on meteorological information collected by DGA stations in Puerto Cisnes and Puerto Aysén, which have equivalent climate patterns to Exploradores river basin, and are 183 and 114 km away from Exploradores. Both stations report a 25% decrease of precipitation if the period 1958 – 1987 compared with 1988 – 2017. A similar decrease in precipitation has also been reported

by a similar study, although further north, affected by the same climatic tendency (Batalla *et al.*, 2018).

Regarding a potential decrease of the glacier- and snow-melt, this could be due to the rising of the isotherm, which yields lower snowpack during accumulation season and decreased melt-waters during the warmer months. This tendency has been established for most of central and southern Chile, including the Patagonia regions of Aysén and Magallanes (Garreaud *et al.*, 2013). A further process potentially responsible for the observed decrease of active channel width could be a reduction of sediment supply due to the rapid recolonization of vegetation on burned areas in the basin and in the proglacial areas. Unlike in other fire-impacted parts of Aysén Region, in the Exploradores basin, this practice has not been as recurrent so the landscape has been able to regenerate after the initial disturbances in the 60-70's. However, positive fire feedbacks (Paritsis et al., 2015) can increase the likelihood of fires in future, and the natural regeneration could have facilitated invasive species to colonize the area. Fire scars are hard to be recognized in the historical aerial photography, and field observation reveals that only little portions of the basin were burned in the past.

In the nearby Murta River basin, Tranmer *et al.* (2018) observed a similar pattern of river narrowing and reduction of braiding parameters. They attributed this dynamic to a diminished sediment load due to glacial lake trapping, hanging valley recession, sediment sorting and armoring in rill, tributary, and main channel environments, and restricted channel access to debris cones and toe slope sediments. It is likely that the main driver of fluvial morphological changes in the Exploradores river network is climatic due to the exceptionally low levels of human intervention in most of the basin, although landslides and GLOFs (related in turn with climate change) can also drive local channel changes. Dynamics such as those described for the Murta River basin are also plausible explanations in the Exploradores River basin, as it constitutes the northern limit of the Northern Patagonia Icefield. The retreat of glaciers forms pro-glacial lakes, such as the one in front of the Grosse Glacier, which trap glacial sediment input to the main river.

Future trends in the Exploradores river basin

The Exploradores River basin is a privileged site to study fluvial processes and dynamics in a nearly pristine environment. So-called natural or reference conditions, prior to anthropic disturbances are often needed to set standards and objectives for river management and restoration but are not observable anymore in most mountainous areas of the Earth (e.g. Comiti, 2012). Even in southern Patagonia, where the legacy of human occupation is lighter and more recent, a recent study of the degree and scope of human influence in the Chilean Patagonia concludes that there is a significant spatial overestimation of the remaining undisturbed natural areas (Inostroza *et al.*, 2016). Despite low population densities and extensive conservation designations, a major share of the total terrestrial surface has been altered by a certain degree of human activities (such as extensive forest fires). The Magellan's Region shares some characteristics with the Aysén Region, however the latter experienced a later and more gradual human colonization because of its geographical isolation.

Although the pervasive role of human activities in shaping the landscape and determining land surface processes (e.g. Tarolli, 2016), the Exploradores River basin's sparse inhabitants, large percentage of intact native vegetation and limited terrestrial connectivity are crucial attributes that allow us to consider it as a mostly pristine landscape (Mittermeier *et al*., 2003). The basin is also located within the area reported by a local study as the total extent of potential intact forested watersheds (IFW; Astorga *et al*., 2018). This is relevant because, although there is general agreement on the intrinsic value and the ecosystem services provided by pristine forests (or primary, ancient, old-growth), IFW are much more scarce territorial units and therefore more threatened.

The geomorphological fluvial characterization presented in this study is to be considered a starting point for further investigations on the nature, processes, and dynamics of fluvial forms in a remote and mostly undisturbed fluvial system. Our results could serve as a basis to reconstruct past flooding events and better understand response to floods and decreasing frequency of floods. For example, nearby Murta River basin shows a stable flow regime (Tranmer *et al.*, 2018), which allows for gradual adjustment of channel dimensions to prevailing hydrologic and sedimentologic conditions rather than river responding to periodic extreme floods that maintain an intermittent disturbance regime. Although there are currently no large water bodies dammed by glaciers or moraines within the basin, this may change in the coming decades as the two main glaciers continue to retreat (Exploradores and Grosse). It is likely that the periodic plugging of the frontal pro-glacial lake in Exploradores Glacier will cause smaller flood events that may affect the Deshielo River and its surroundings.

The climate change is accelerating glacial ablation, and the Exploradores basin hosts few glaciers of the Northern Patagonian Icefield that are under a general recession trend, with consequences on glacier melt runoff, freshwater supply to the Cupquelán fiord, morphodynamics of the Exploradores river and estuary, and also implications for biodiversity on riparian corridors. Biodiversity will also be affected by the arrival of exotic species as human flux within the basin increases. Currently, the main vegetal invasive species present in riparian corridors are introduced willow (*Salix fragalis/alba*) and herbaceous lupine (*Lupinus polyphyllus*). The impact of introduced willow has also been identified in the neighbor Baker River basin. There are other herbaceous species present in grasslands associated with livestock, however willow and lupine generate important impacts on fluvial morphology and dynamics. Willows are currently present along Norte River but not past Bayo Lake, whereas lupine has advanced along so far as Grosse Glacier outlet. These species are indicators of the impact of humans as vectors for invasive species colonization.

More generally, evidence suggests that Chilean rivers will be progressively more threatened by excessive direct and indirect anthropogenic impacts (Andreoli *et al*., 2012). The Exploradores River is at a vertex of its environmental history. The improved connectivity product of the culmination of the bridge in Teresa, which connects the last section of the road to Exploradores Bay, will increase endogenous pressure such as the intensification of tourism activities and development of aquaculture industry. The basin is also affected by exogenous pressures such as the increase in temperature and decreased precipitation due to the climate change. In light of this, stands out the importance of deepening the understanding of such remote areas as they transform.

Final remarks

The current analysis of the Exploradores river network is one of the first attempts to assess the geomorphological characteristics of rivers in Chilean Patagonia, as only a few similar studies exist for basins of the south-austral zone of Chile (Rivers Ñuble, Murta and Baker). A series of field surveys and analysis of multitemporal satellite images allowed to define key patterns related to river morphology within the basin, such as greater sinuosity and braiding index in reaches with lower confinement located in valleys. This characterization contributes to the understanding of the fluvial networks and processes acting over them in a study area with very limited accessibility and virtually no information.

The Exploradores basin experienced only limited and recent human disturbances, and fluvial changes are related almost only to natural climatic or geomorphological processes. Although the basin is affected by GLOF events, including two recent ones in 2015 and 2018, river reaches showed a moderate reduction of active channel width and braiding index over the past 70 years. These changes can be related to a general reduction of rainfall (also reported by Batalla *et al.*, 2018), a decrease of glacier and snow-melt, or a decreased sediment load. Because of its position and very limited human disturbances, the Exploradores basin could represent a suitable site to study fluvial processes and dynamics in nearly reference conditions. Also, because of the very recent increase of connectivity and touristic development, the area is likely to be impacted by direct and indirect disturbances and represent a privileged site for studying the interactions of human activities and the environment in a nearly-pristine system, where more sustainable ways of development could be tested and assessed.

This study highlights the importance of studying fluvial systems in reference basins with relatively low direct anthropogenic disturbances at the basin scale, in terms of relationships between global environmental changes and fluvial forms and processes. Future studies in this and similar basins should also focus on bio-geochemistry cycles, floodplain organic carbon fluxes, and floodplain stock changes with the climate change, especially in glacierized basins.

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TABLES

Table 1. Attributes of the analyzed reaches.

Attribute	Units	Description
Name of the river	text	Name according to IGM
Accessibility	n/a	Low or medium
Length	m	Distance measured along the river axes
Average slope	m m^{-1}	Altitude drop over distance unit
Sinuosity index (Si)	-	Ratio between thalweg length and general planimetric length
Confinement degree (Gc)	%	Percentage of the banks that are not in contact with the floodplain, but with the hill slopes or old floodplains
Floodplain width (Wfp)	m	Width of the low portion of a valley subject to periodic flooding (average of multiple measurements taken at equally spaced intervals)
Active channel width (Wac)	m	Width of the unvegetated reach (average of multiple measurements taken at equally spaced intervals)
Baseflow channel width (Wbf)	m	Width of the water (excluding bars) (average of multiple measurements taken at equally spaced intervals)
Braiding index (Bi)	count	Number of channels per section
Confinement index (Ic)	ratio	Ratio between the floodplain width and the active channel width
Morphological units	count	Glaciers, islands, oxbow lakes
Human interventions	count	Bridges, lateral defenses
Drainage area	km^2	Surface of the drainage basin
Maximum elevation	m asl	Maximum elevation within the basin
Minimum elevation	m asl	Minimum elevation

Table 2. Average morphological attributes of the reaches.

Dominant morphology	A	P	Si	Wfp	Wac	Wbf	Bi
Confined braided	13.51	6.8%	1.09	100	79	32	1.6
Confined single-thread	1.63	14.7%	1.13	20	15	11	1.0
Semiconfined anastomosed	14.43	1.17%	1.21	277	53	42	2.8
Semiconfined braided	8.34	2.2%	1.15	197	122	23	2.3
Semiconfined sinuous	9.58	5.2%	1.20	104	30	17	1.0
Semiconfined sinuous with alternate bars	10.93	0.7%	1.28	100	55	21	1.8
Semiconfined straight	1.32	3.0%	1.07	41	20	9	1.0
Semiconfined wandering	0.64	8.8%	1.14	120	30	20	2.5
Unconfined anastomosed	36.62	1.13%	1.19	528	78	47	2.2
Unconfined sinuous	24.17	0.9%	1.39	321	48	24	1.3
Unconfined with alternate bars	6.29	0.7%	1.25	500	40	20	6.0
Unconfined straight	0.34	4.6%	1.12	100	10	8	1.0

A: drainage area in km^2; P: average reach slope; Si: sinuosity index; Wfp: floodplain width (m); Wac: active channel width (m); Wbf: baseflow channel width (m); Bi: braiding index or number of channels per section

Table 3. Morphological attributes of the reaches selected for the morphological change analysis

Reach code	Sector	River name	L	A	P	Bi	Si	Wfp	Wac	Wbf	Morphology	% G
T_038	Up	Norte	3550	167	0.0067	1.5	1.304	150	70	25	SC alternate bars	0.8%
T_040	Up	Norte	2550	180	0.0086	1	1.269	150	40	30	SC sinuous	0.7%
T_041	Up	Norte	415	183	0.0457	1	1.092	30	25	20	C single-thread	0.7%
T_042	Up	N/N	1851	5	0.2199	1	1.082	10	8	6	C single-thread	0.0%
T_043	Up	Norte	2178	194	0.0197	2	1.130	130	50	30	C braided	0.7%
T_044	Up	Norte	938	195	0.0159	1.5	1.059	150	50	30	SC sinuous	0.7%
T_052	Up	Norte	4836	231	0.0016	1.5	1.243	400	80	30	UC sinuous	1.1%
T_128a	Down	Oscuro	2150	337	0.0023	1	1.283	215	85	50	SC sinuous	0.0%
T_129a	Down	Exploradores	3663	1143	0.0029	1	1.105	195	120	70	SC sinuous	8.5%
T_163	Down	Teresa	3914	249	0.0008	1	1.133	400	50	30	SC sinuous	0.9%
T_170	Down	Exploradores	6960	1418	0.0013	1.5	1.209	1000	150	100	U sinuous	7.0%
T_171	Down	Exploradores	5960	1452	0.0009	2	1.149	1200	170	150	U anastomosed	6.8%

L: length in kilometers; A: drainage area in km^2; P: average reach slope; Bi: braiding index or number of channels per section; Si: sinuosity index; Wfp: floodplain width (m); Wac: active channel width (m); Wbf: baseflow channel width (m); %G: drainage area glacierized. Measures presented for Lp, Lb and La correspond to the most recent period of study (2010/2011)

FIGURE CAPTION

Figure 1. Location (a) and map of land use and relevant features (b) of the Exploradores basin.

Figure 2. Chronology of the available aerial photographs for the Exploradores basin.

Figure 3. Stages in road construction, land-ownership and interventions along main the main valley of the Exploradores basin.

Figure 4. Photos of some of the few structures and interventions along the road within the Exploradores basin showing a bridge over the Exploradores river after the conference with the Teresa River (a, taken in December 2017, see location on Figure 5), a large culvert in the Norte River (b, taken in May, 2016, see location on Figure 5), flow deflectors at the confluence of the Exploradores, Teresa, and Oscuro rivers where an emergency landing area is located (c, taken in May, 2016, see location on Figure 5), and riprap embankments in a small tributary of the Exploradores River (d, photo taken in April, 2016).

Figure 5. Hydro-morphological characterization of the hydrographic network of the Exploradores basin (C: confined; SC: semiconfined; UC: unconfined).

Figure 6. Comparison of (a) baseflow channel width (b) active channel width, (c) floodplain width, (d) braiding index, (e) sinuosity index and (f) slope, on river reaches characterized by different confinement (C: confined; SC: semiconfined; UC: unconfined). The line within each box indicates the median value, box ends are the 25^{th} and 75^{th} percentiles, whiskers ends are the 10^{th} and 90^{th} percentiles, and lose points are outliers and extreme values.

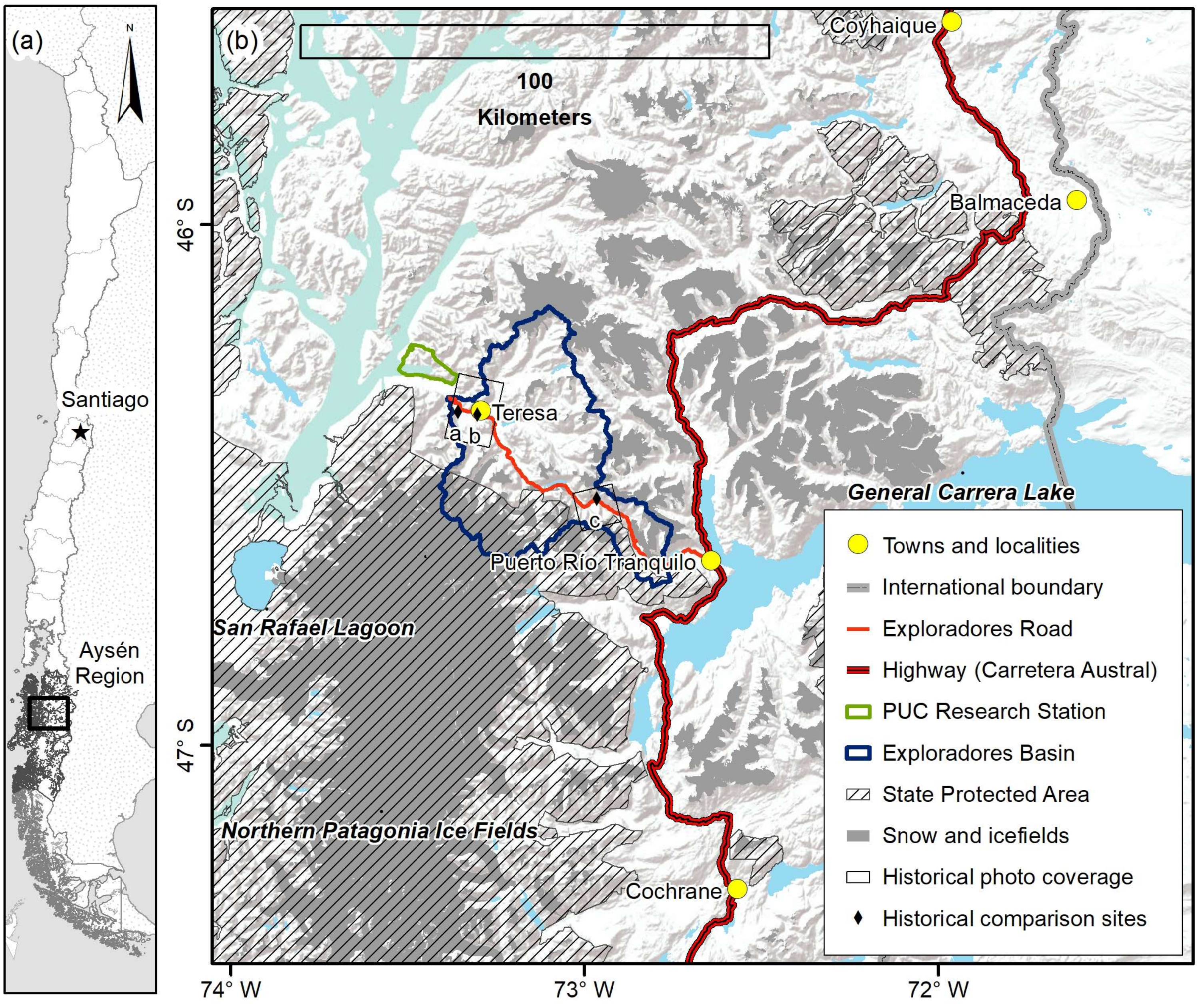
Figure 7. Relationships between drainage area and active channel width of each reach within the Exploradores basin. The reaches are grouped in terms of confinement (a) and presence of glacierized surface in the basin (b).

Figure 8. Comparison of aerial photography and satellite images taken in 1943, 1979/84, 1997 and 2010/10 in two downstream (a and b) and one upstream sector (c) of the Exploradores River basin. The location of the locations a, b, and c is depicted on Figure 1.

Figure 9. Changes in relative baseflow channel width (a), active channel width (b), and braiding index (c) from 1943 to 2011 for reaches included in the analyzed sectors, classified in terms of lateral confinement.

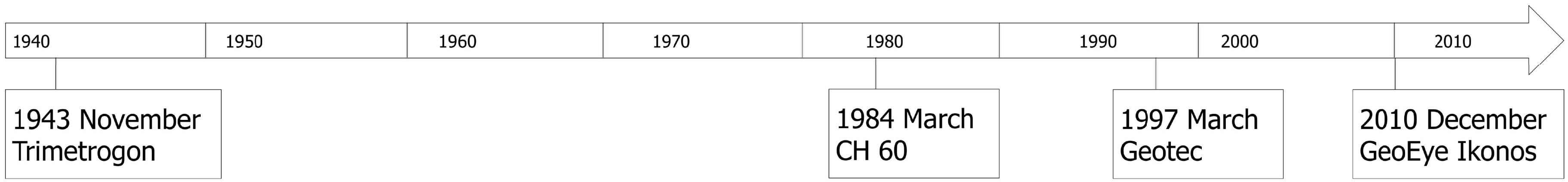
Figure 10. Equivalent oblique views from 1943 aerial photograph and 2018 satellite image of pro glacial lake at Grosse Glacier that suffered a GLOF around 1970. The most important features are named on the 1943 photo.

Figure 11. The Deshielo River suffered a GLOF in April 2018. The photos are taken from the bridge over the river (a) before the event (April 29, 2016), (b) during the event (April 18, 2018) and (c) after the event (April 30, 2018). Photo were taken from the point depicted on Figure 5 by (a) Camila Bañales-Seguel, (b) Ricardo Rojas, (c) Francisco Croxatto.

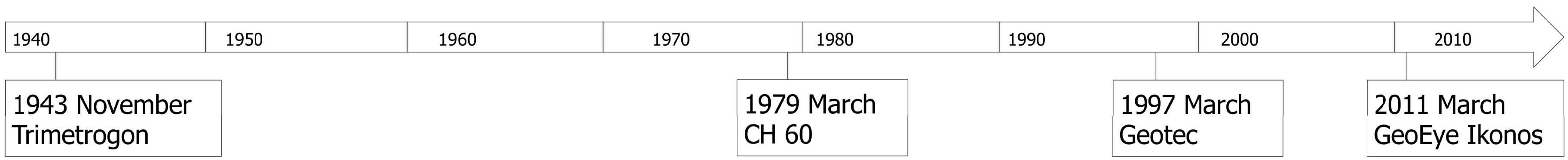


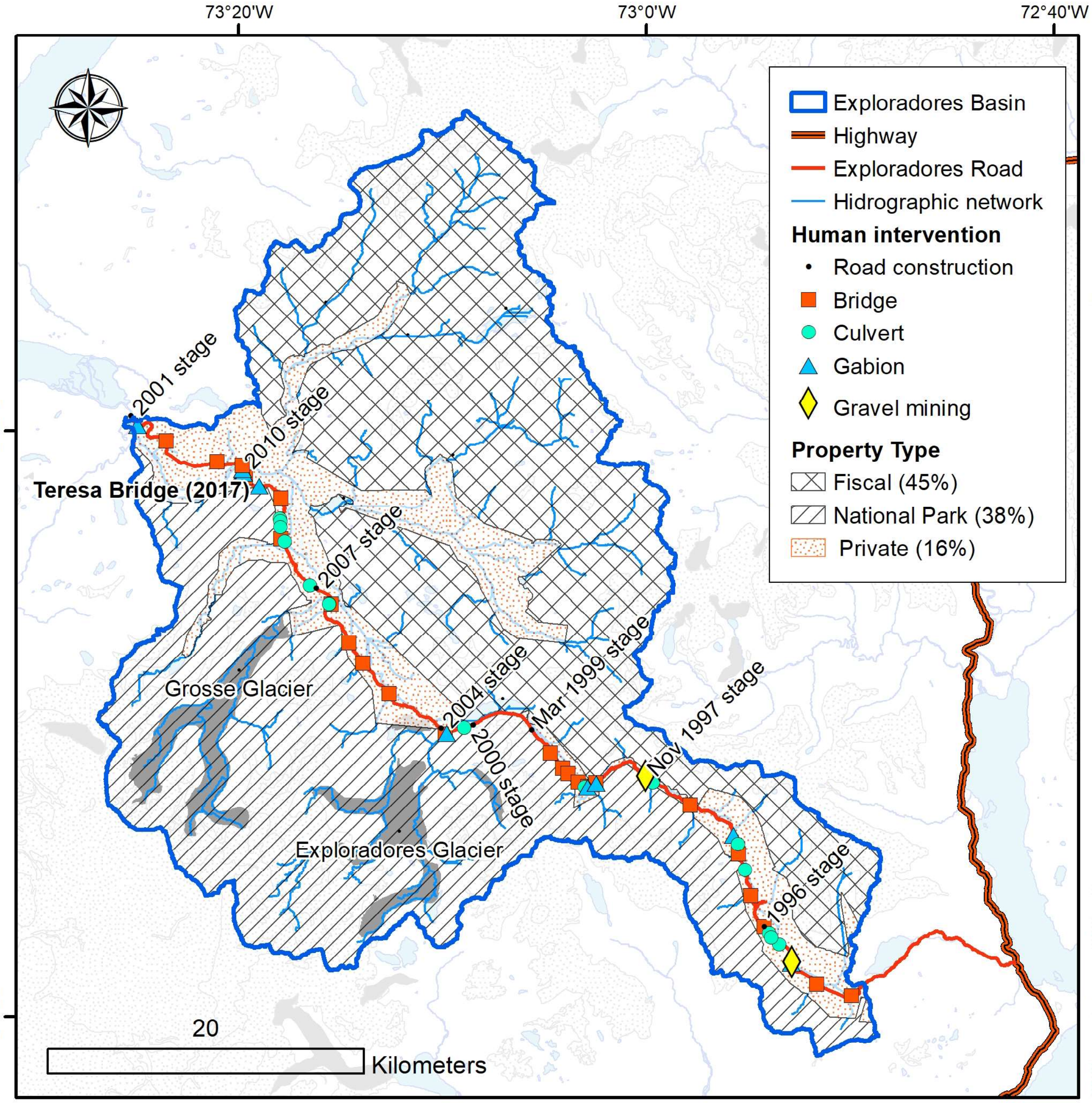
(a)
N
Santiago
Aysén Region
(b)
100
Kilometers
Coyhaique
Balmaceda
Teresa
a
b
c
Puerto Río Tranquilo
General Carrera Lake
San Rafael Lagoon
Northern Patagonia Ice Fields
Cochrane
46° S
47° S
74° W
73° W
72° W
Towns and localities
International boundary
Exploradores Road
Highway (Carretera Austral)
PUC Research Station
Exploradores Basin
State Protected Area
Snow and icefields
Historical photo coverage
Historical comparison sites

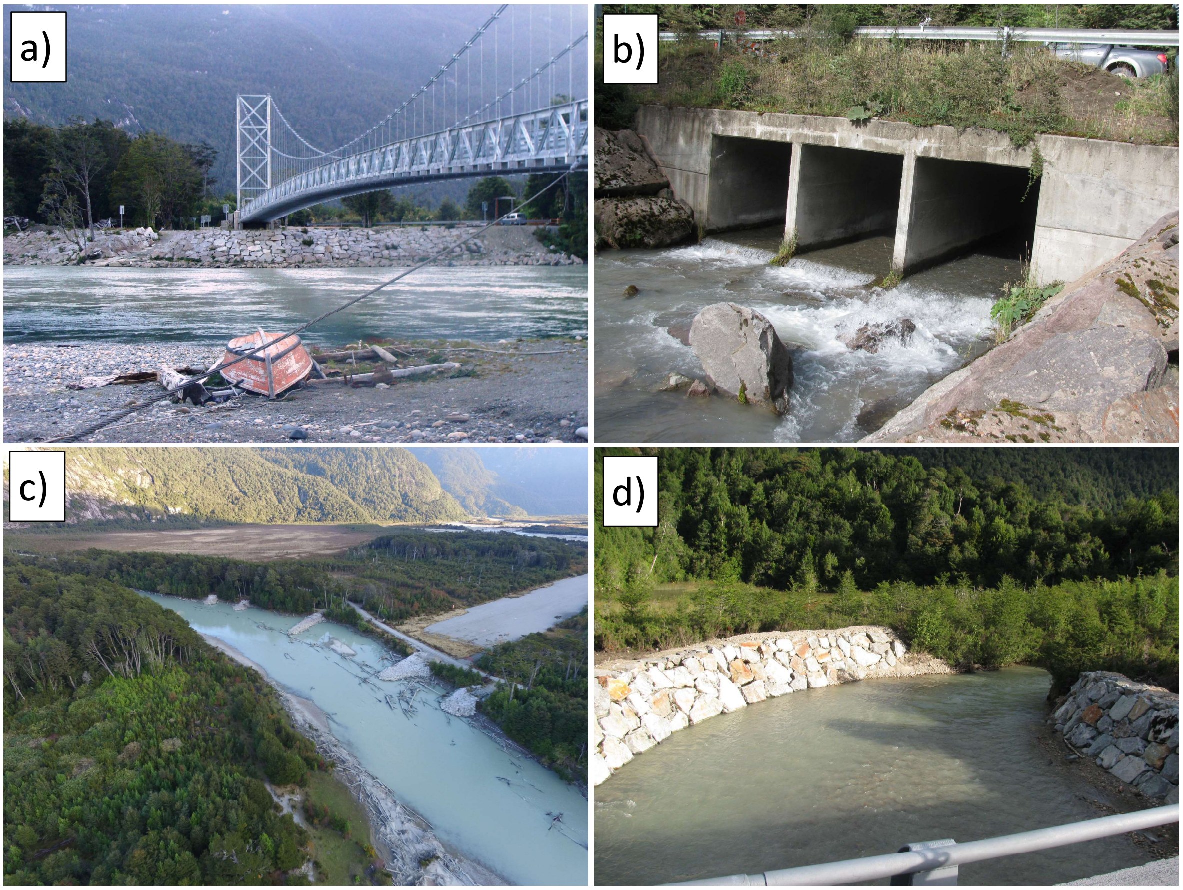
Upstream sector: East of Bayo Lake

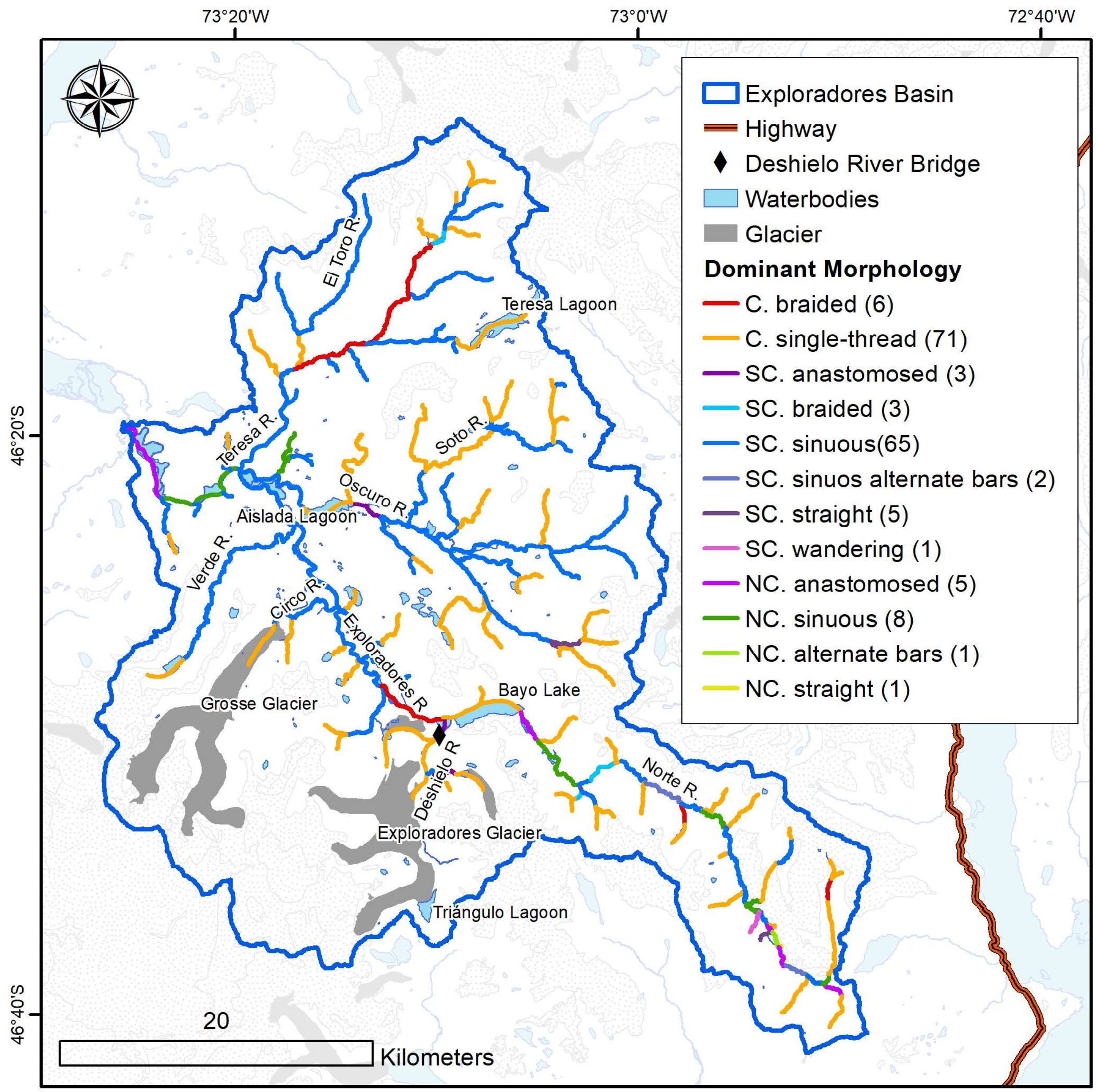


Downstream sector: Confluence of three rivers

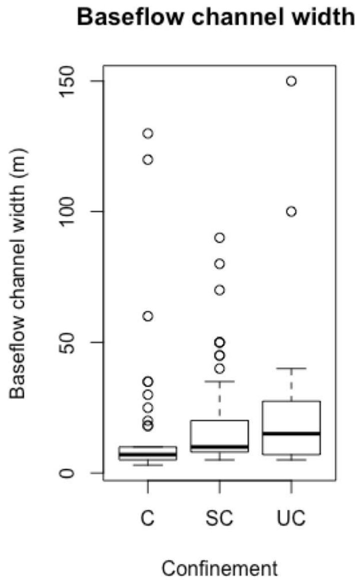


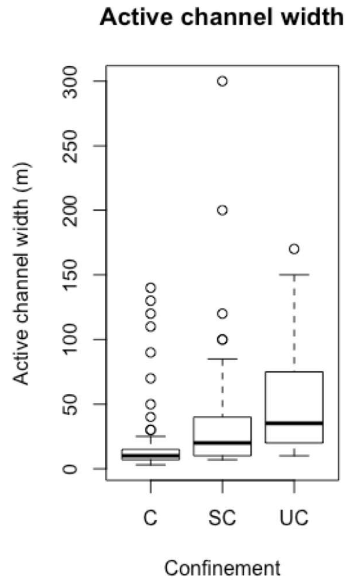

73°20'W
73°0'W
72°40'W
46°20'S
46°40'S
Exploradores Basin
Highway
Exploradores Road
Hidrographic network
Human intervention
Road construction
Bridge
Culvert
Gabion
Gravel mining
Property Type
Fiscal (45%)
National Park (38%)
Private (16%)
2001 stage
2010 stage
Teresa Bridge (2017)
2007 stage
Grosse Glacier
2004 stage
Mar 1999 stage
2000 stage
Nov 1997 stage
Exploradores Glacier
1996 stage
20
Kilometers

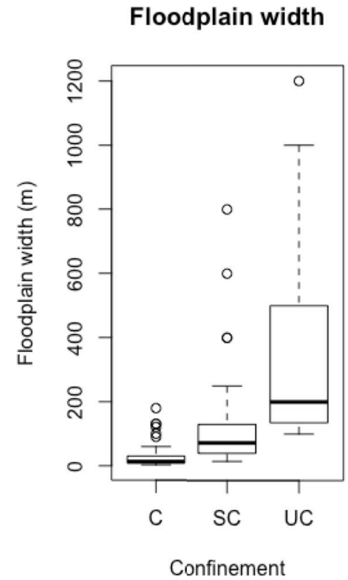

a)
b)
c)
d)

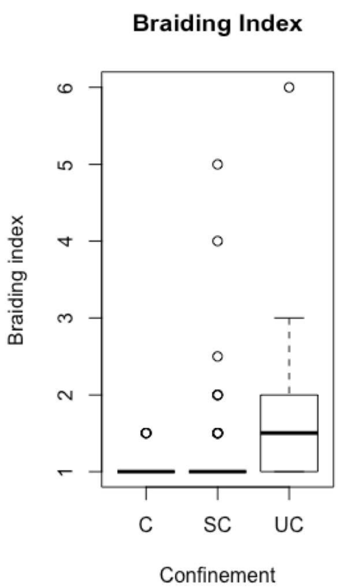


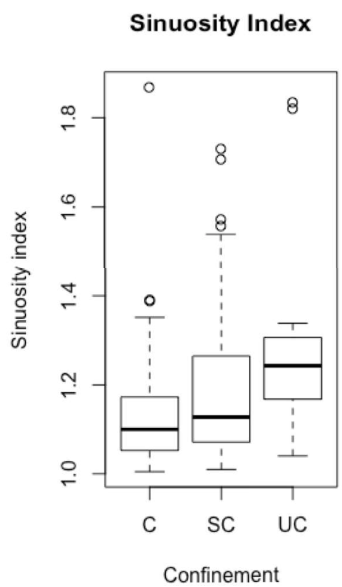
73°20'W
73°0'W
72°40'W
46°20'S
46°40'S
Exploradores Basin
Highway
Deshielo River Bridge
Waterbodies
Glacier
Dominant Morphology
C. braided (6)
C. single-thread (71)
SC. anastomosed (3)
SC. braided (3)
SC. sinuous(65)
SC. sinuos alternate bars (2)
SC. straight (5)
SC. wandering (1)
NC. anastomosed (5)
NC. sinuous (8)
NC. alternate bars (1)
NC. straight (1)
El Toro R.
Teresa Lagoon
Soto R.
Teresa R.
Oscuro R.
Aislada Lagoon
Verde R.
Circo R.
Exploradores R.
Bayo Lake
Grosse Glacier
Deshielo R.
Norte R.
Exploradores Glacier
Triángulo Lagoon
20
Kilometers

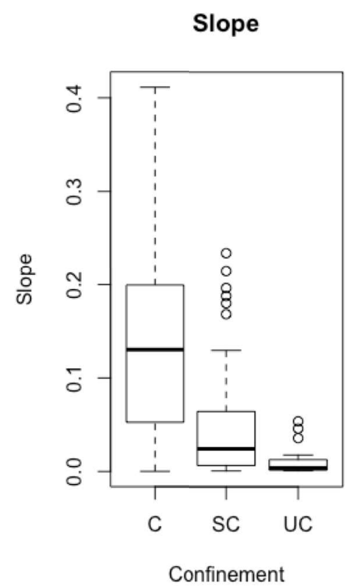

Baseflow channel width
Baseflow channel width (m)
0
50
100
150
C
SC
UC
Confinement
(a)

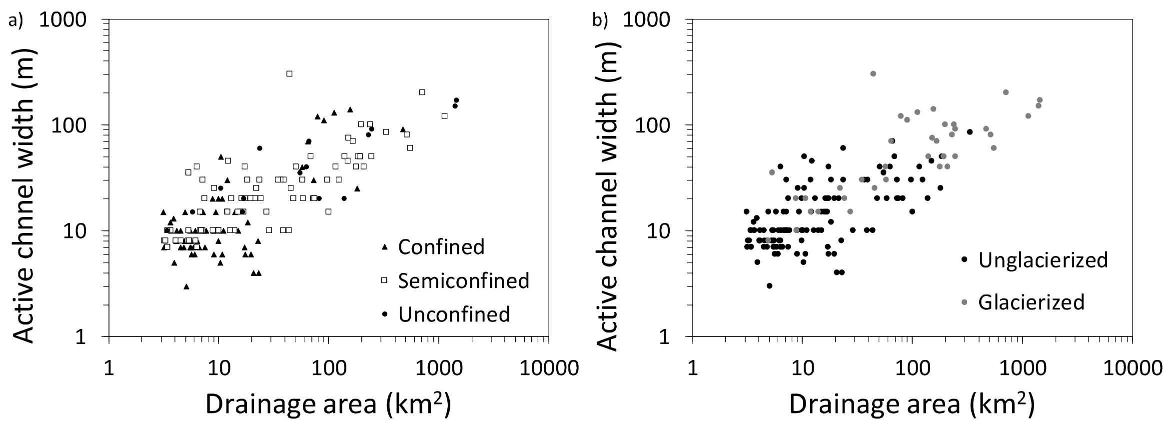

Active channel width
Active channel width (m)
0
50
100
150
200
250
300
C
SC
UC
Confinement
(b)


Floodplain width
Floodplain width (m)
0
200
400
600
800
1000
1200
C
SC
UC
Confinement
(c)

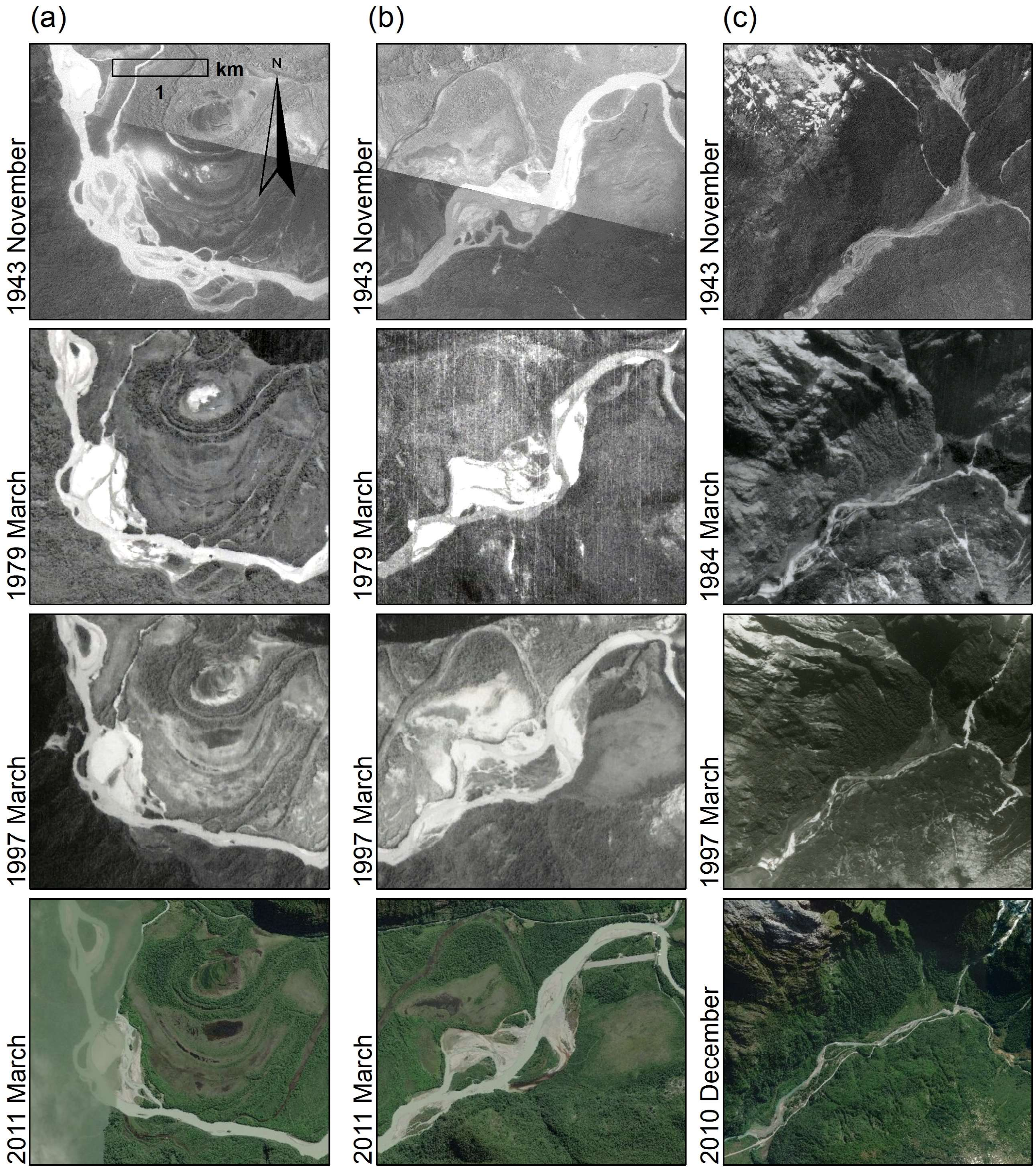

Braiding Index
Braiding index
1
2
3
4
5
6
C
SC
UC
Confinement
(d)

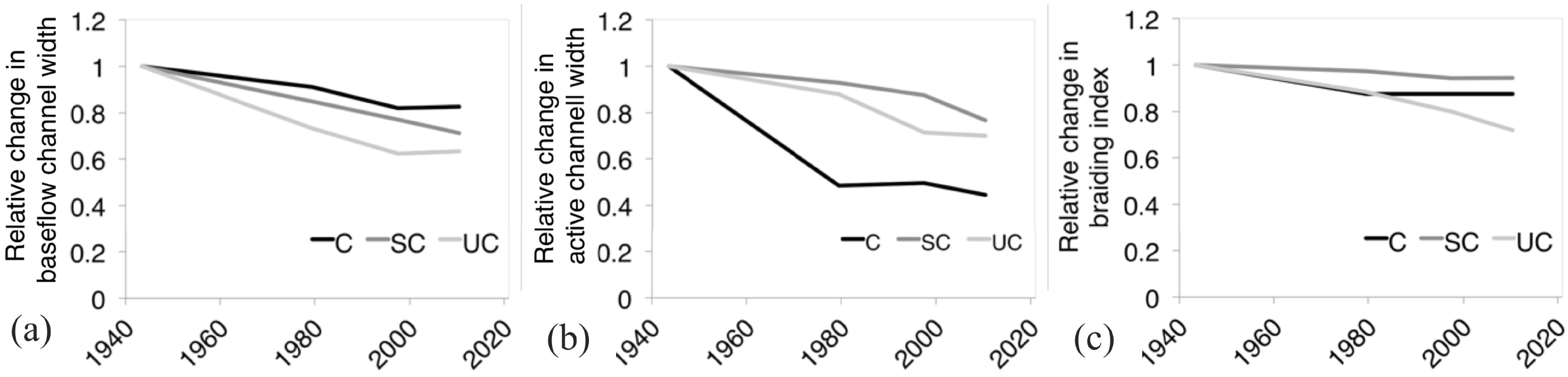

Sinuosity Index
Sinuosity index
1.0
1.2
1.4
1.6
1.8
C
SC
UC
Confinement
(e)

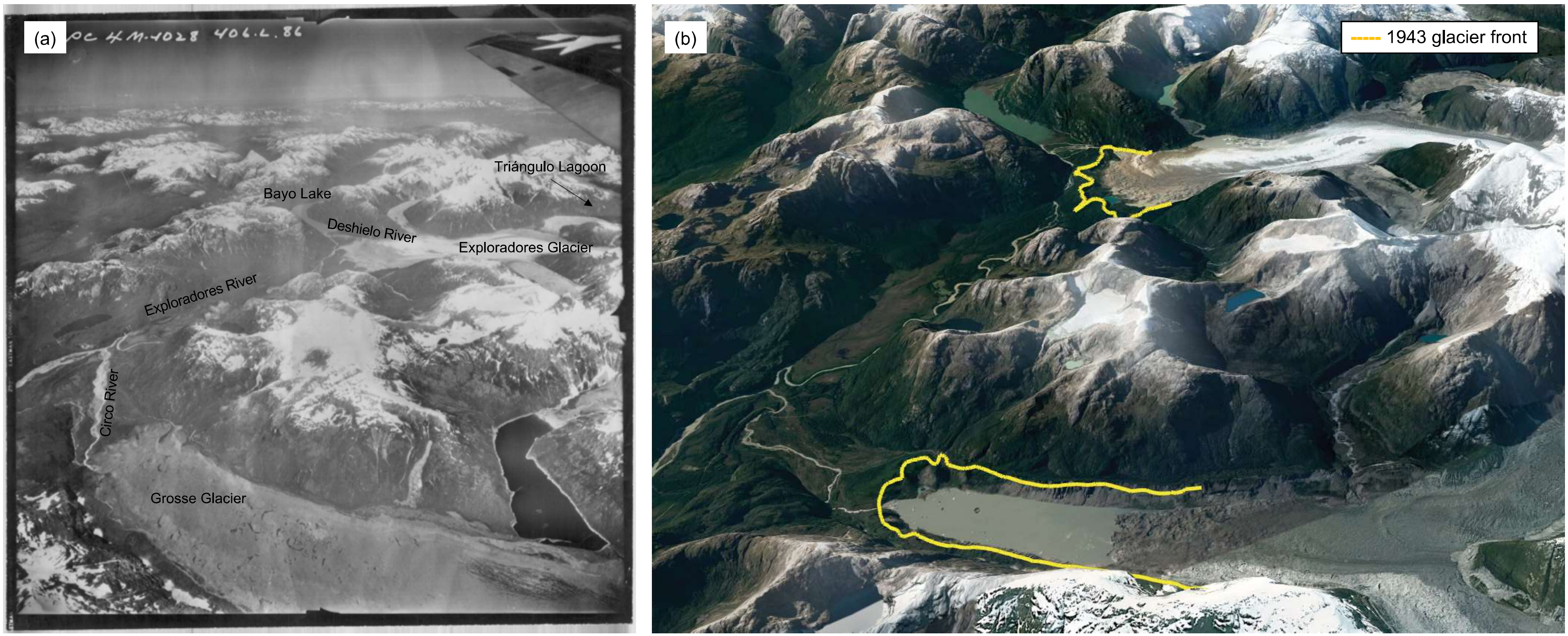

Slope
Slope
0.0
0.1
0.2
0.3
0.4
C
SC
UC
Confinement
(f)



a)
Active chnnel width (m)
Drainage area (km²)
Confined
Semiconfined
Unconfined
1
10
100
1000
10000
b)
Active channel width (m)
Drainage area (km²)
Unglacierized
Glacierized


(a)
(b)
(c)
km
1
N
1943 November
1943 November
1943 November
1979 March
1979 March
1984 March
1997 March
1997 March
1997 March
2011 March
2011 March
2010 December


Relative change in baseflow channel width
1.2
1
0.8
0.6
0.4
0.2
0
1940
1960
1980
2000
2020
C
SC
UC
(a)
Relative change in active channell width
(b)
Relative change in braiding index
(c)


(a)
PC HM-1028 406.L.86
Triángulo Lagoon
Bayo Lake
Deshielo River
Exploradores Glacier
Exploradores River
Circo River
Grosse Glacier
(b)
1943 glacier front

(a) (b) (c)